Durability of concrete with recycled coarse aggregates: influence of superplasticizers

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Abstract: The use of recycled aggregates in concrete production can significantly contribute to its sustainability but it may also jeopardize its durability. The use of superplasticizers may compensate for this performance handicap by contributing to the improvement of the inner structure of this type of concrete.

The main goal of this study is to evaluate the effect of standard and high-performance superplasticizers on the key durability-related properties (shrinkage, water absorption by immersion and by capillarity, carbonation and chloride penetration resistance) of concrete made with different percentages of recycled coarse aggregates from crushed concrete, and compare the findings with the corresponding effect on conventional concrete.

The overall conclusion is that recycled aggregate concrete is more susceptible to deterioration due to environmental conditions affecting this concrete's durability performance more than that of conventional concrete. But introducing superplasticizers in recycled aggregates concrete can help to enhance the concrete's performance and offset this higher susceptibility.

Subject headings: Recycling, aggregates, concrete, concrete admixtures, durability

Author keywords: Recycled coarse aggregates, concrete, superplasticizers, shrinkage, water absorption, carbonation resistance, chloride penetration resistance

Abbreviations: CDW - construction and demolition waste; NA - natural aggregates; RA - recycled aggregates; RAC - Recycled aggregates concrete; RCA - recycled coarse aggregates; RC - reference concrete; *SP0 - mix without superplasticizer; SP1 - standard superplasticizer; SP2 - high-performance superplasticizer

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INTRODUCTION

The future of the construction industry should include causing the least possible harm to both users and the environment. In a search for alternative solutions, the use of construction and demolition waste (CDW) to produce new concrete is becoming an obvious choice. About 25% of all waste generated in the EU arises from CDW and 78% of this is concrete, bricks, tiles, etc. (Brodersen et al. 2002). CDW has a huge potential for recycling, and this can contribute to reducing the economic and environmental costs of removal to dumping grounds and, more importantly, the excessive demand for natural resources, especially natural aggregates (NA), for construction works. There is a general preconception about the negative influence of using recycled concrete aggregates in concrete production. However, a number of publications (Etxeberria et al. 2007, Evangelista et al. 2010, Kou et al. 2011) have studied the mechanical and durability properties of recycled aggregates concrete and the results contradict this idea. To better understand the mechanical and fresh-state properties of concrete it is essential to study its durability since this measures its long-term performance.

EXPERIMENTAL PROCEDURE

Materials

The NA used in this study was crushed limestone (coarse aggregate) and river sand (fine aggregate). The RA were produced by crushing a demolished reinforced slab (compressive strength over 40 MPa). The aggregate properties are listed in Table 1.

The superplasticizers were: a standard superplasticizer henceforth called SP1, whose chemical basis is a blend of organic polymers and additives; a high-performance superplasticizer henceforth called SP2, whose chemical basis is an aqueous solution of modified polycarboxylates. The content of admixtures in each mix had to be adjusted to achieve the target workability and to maintain the mixes’ characteristics, such as the size distribution, the *w/c* ratio, cement content, etc., without having to add extra water.

Concrete mix composition and mixing method

The reference concrete (RC) was produced in lab, according to NP 206-1 (2005). The target 28-day compressive strength in cubes (150 mm) was 35 MPa and the slump (Abrams cone) was approximately 85 mm. The RC detailed composition is presented in Table 2.

This experimental program determined the influence of superplasticizers (SP1 and SP2) on RA concrete, with three RA contents (100%, 50% and 25%). The mixes' characteristics and compositions (based on the Faury method, assuming a target slump of 80 ± 10 mm) are summarized in Table 2. The material's particle density is as follows: sand - 2544, cement - 3110, RA - 2421, NA - 2632 and water - 1000 kg/m^3.

The NA was primarily and secondarily crushed and the RA was only primarily crushed (as there was no secondary crusher in the laboratory facilities). As discussed by Matias et al. (2013) the crushing process may have an influence on the aggregates shape and texture and thus on the concrete properties.

As the water absorption of RA is higher than that of NA, there will tend to be less free water in the mixes with RA. To ensure there is enough mixing water for the cement hydration and that the effective *w/c* ratio remains the same, extra water must be added to these mixes. Although the *w/c* ratio increases, it is not expected to affect the concrete's performance as the additional water will be absorbed by the RA (Ferreira et al. 2011). The amount of extra water was determined considering the amount needed to raise the moisture content of the RA in the air-dry state (2.88%) to the saturated state (4.12%). The result was 29.21 L/m^3 of RA and 12 L/m^3 of concrete, for 100% of RA. The SP1 and SP2 contents were determined in order to maintain the slump approximately equal to the one of the corresponding mix without superplasticizers (Table 2).

Tests on concrete mixes

The testing methodology used in this research is based on the European and Portuguese standards specified below. The method to determine workability is specified in NP EN 12350-2 (2009) and the fresh concrete's specific density was determined according to NP EN 12350-6 (2009). The compressive strength (NP EN 12390-3 2009) specimens were 15 cubes with 150 mm^3 per mix for various ages. The shrinkage (LNEC E 398 1993) specimens were 2 prisms measuring 150 x 150 x 550 mm per mix and the measurement was performed using electric extensometers. The water absorption by immersion (LNEC E 394 1993) specimens were 4 cubes measuring 100 mm^3 per mix. The water absorption by capillarity (LNEC E 393) specimens were 2 prisms measuring 100 x 100 x 200 mm per mix. The determination of the carbonation (LNEC E 391 1993) resistance required 2 cylindrical specimens per mix with a base diameter of 150 mm and height of 40 mm, and the determination of the chloride penetration (NT BUILD 492 1999) required 3 cylindrical specimens per mix with a base diameter of 100 mm and height of 50 mm.

EXPERIMENTAL RESULTS AND DISCUSSION

Fresh concrete properties

Workability-When the same superplasticizer content is added to mixes with SP1 and the effective *w/c* ratio is kept constant, a decreasing trend of concrete workability was observed as the RCA ratio increased, as seen in Table 3. Pereira et al. (2012), although for fine RA concrete, also found a decline in efficiency for a similar type of superplasticizer with the incorporation of the RCA.

The use of 0.5% of cement weight in the 100RACSP2 mix led to a slump of 155 mm, considerably above the target slump of 80 ± 10 mm. As expected the high-performance superplasticizer SP2 was more effective in achieving the target workability of concrete with RA than the standard superplasticizer SP1 (Pereira et al. 2012). The same workability in the 100RACSP2, 50RACSP2 and 25RACSP2 mixes was achieved by reducing the ratio of SP2, as shown in Table 3. The ratio of SP2 was also lower for lower percentages of RA, but it did not decrease linearly.

Specific density - As expected, the concrete's specific density tends to decrease with the incorporation ratio of RA, due to the lower particle density of RA in comparison to NA. However, the differences due to the use of superplasticizers are insignificant. Considering mixes with the same incorporation ratio, with or without superplasticizers, the results were very similar (except for the 25RACSP1 mix which is inconsistent with the general results, probably because it had a slightly higher SP1 content than necessary, as highlighted by the slightly higher slump in Table 3).

Hardened concrete properties

Compressive strength - For a 100% incorporation ratio the compressive strength showed losses of 5.9% for SP1 and 3.9% for SP2; for a 50% incorporation ratio no loss was registered, and for a 25% incorporation ratio losses were 5.8% for SP1 and 3.5% for SP2 (Fig. 1). The proximity of the results can be explained by the addition of superplasticizers. They generally induce a greater compactness in the mix, contributing to compensate for the strength loss due to the incorporation of RA. They may also compensate, at least partially, the effect of a higher w/c ratio related to the need to add extra mixing water to offset the potential water absorption of RA (Pereira et al. 2012).

The compressive strength was also analysed as a function of the curing time for the RC, 100RACSP1 and 100RACSP2 mixes (Fig. 1). Although the early strength of the mixes with RA and superplasticizers is lower than that of RC, the compressive strength curves increase continuously until 28 days.

Shrinkage - The results showed higher shrinkage in the first days of the test and stabilization only after 20 days, as shown in Fig. 2. During this initial period, the balance between the repulsive electrostatic forces and the attractive capillary forces is stronger for the latter, causing marked cracks to appear. After that period of time, shrinkage continues to increase, although at a decreasing rate, where the chemical reactions progress, decreasing the repulsive forces between the solid particles (Morin et al. 2001). The presence of superplasticizers induces air entrapment and micro bubbles formation during mixing by lowering the surface tension of the interstitial fluid. The study concluded that the higher the amount of superplasticizer, the larger the volume of entrapped air, favouring the occurrence of higher shrinkage. So, it was expected that 100RACSP1 and 100RACSP2 (mixes with plasticizers and recycled aggregates) would have higher shrinkage than RC (mix without plasticizer or natural aggregates). The 100RACSP1 mix had higher shrinkage than the 100RACSP2 mix, not only due to the fact that the former has a higher content of superplasticizer for the same workability, but also due to the type of plasticizer used. Polycarboxylic polymers, the main component of SP2, are more effective in increasing the compatibility of the concrete mix than the lignosulphonate polymers from SP1. Because the porous space in 100RACSP2 is lower, the shrinkage phenomenon is less pronounced than in 100RACSP1. This shows that admixtures with greater water reducing power can control this phenomenon better, even with high ratios of RA.

Water absorption by immersion - The results were 13.7% for RC, 17.2% for 100RACSP0 and 100RACSP1 and 17.5% for 100RACSP2. As expected, that the RA concrete had a higher water absorption level than the RC, due to the RA's high open porosity. Neither the addition of superplasticizers (100RACSP0 vs. 100RACSP1 and 100RACSP2), nor the type of superplasticizers (100RACSP1 vs. 100RACSP2) seem to affect the water absorption because all RA concrete mixes absorbed roughly 17% of water.

Water absorption by capillarity - The RA concrete had the highest capillary water absorption values, due in large measure to the high porosity of the adhered mortar portion of the RA. The superplasticizers increased the water absorption by capillarity of the RA concrete, approximately 30% (100RACSP0 vs. 100RACSP1 and 100RACSP2). There was no influence of the type of superplasticizer, since the water absorption by capillarity increase was 80% for both mixes (RC vs. 100RACSP1 and 100RACSP2) and the respective curves were almost identical (Fig. 3). The inner structure formation of hardened concrete is related to the hydration delay caused by the superplasticizers and their action on the coagulation structure of the fresh paste, associated with the connection of a continuous capillary pore network. In the Sakai et al. study (2006), the degree of the cement's hydration at 28 days revealed to be almost the same, whether using lignosulphonate or polycarboxylic based superplasticizer, suggesting that the type of superplasticizer does not exert influence on the late stage of the cement hydration, as shown in the obtained results.

Carbonation resistance - Significant differences were observed between mixes (100RACSP1 and 100RACSP2 vs. RC) in terms of the type of evolution of the carbonation depth vs. the exposure time (Fig. 4). The addition of superplasticizers influenced the susceptibility to carbonation, especially at the beginning, when the RC mix registered the highest carbonation depths. In the long-term, the efficiency of SP1 (standard superplasticizer) seems to decrease and carbonation depths greater than that of the RC were found. Nevertheless, superplasticizers help to produce a more homogeneous concrete, with fewer discrepancies than the RC. The type of superplasticizer has also exerted some influence on the carbonation resistance. Different superplasticizers act distinctively with cement components, such as C_3S and C_3A, during the hydration process. The adsorption of superplasticizers can hinder the growth of the mix crystals, changing their morphology, so that crystals become denser on the surface of cement particles, linking the cement particles in the cement paste. This way the hydration products become more compact to resist carbonation. Studies concluded that the greater the water reducing capacity of the superplasticizer the less carbonation occurs (100RACSP2 vs. 100RACSP1) (He et al. 2012).

Although the water absorption by capillarity is higher for RA concrete than for RC, and therefore it would be expected that the carbonation depth would follow the same trend, results were the opposite. According to Buyle-Bodin et al. (2002), a higher internal humidity content associated to a lower porosity would allow a slower water evaporation, similar to an extended cure and may partially contribute to decrease the carbonation depth. The introduction of superplasticizers, to a certain extent, delays the curing time for the hydration of the cement, which is equivalent to a prolonged cure, improving the carbonation depth results for mixes using superplasticizers.

Chloride penetration resistance - The average diffusion coefficient (and chloride penetration depth) was 7.30E-12 m^2/s (15.77 mm), 7.11E-12 m^2/s (15.33 mm) and 5.97E-12 m^2/s (13.13 mm) for RC, 100RACSP1 and 100RACSP2, respectively. The results showed that superplasticizers affect this parameter positively by helping to compact the cement paste and hinder chloride penetration that would otherwise have been higher because of the RA. But the influence of the superplasticizers differed in terms of the results. While the SP1 (standard superplasticizer) achieved a depth similar to (even though slightly lower) than that of the RC (variation 2.5%), the SP2 (high-performance superplasticizer) achieved a lower depth and thus opposed chloride penetration more efficiently (18.1%). Because SP2 contains polycarboxylic polymers, whose dispersion mechanism is mainly by steric hindrance, the dispersion effect is higher than that of SP1, which acts by electrostatic repulsion and comprises lignosulphonate polymers (Pereira et al. 2012). The higher the dispersion capacity of the superplasticizer, the higher the number of cement particles available to interact with water is; i.e. for the same amount of cement and water and if the mix is properly dispersed, SP2 is able to have a higher yield, in comparison to SP1, and thus it may contribute to the increase of the mix strength and compactness, thus improving, for this specific case, the chloride penetration of 100RACSP2. For future use, it is concluded that, depending on the RA incorporation ratio, the superplasticizer characteristics and its content, the chloride penetration will be higher or lower than that of the RC.

CONCLUSIONS

Based on the results of this experimental work, the following conclusions are drawn:

- Neither the concrete's specific density nor the water absorption by immersion or the capillarity properties were influenced by the superplasticizers (in content or type);
- The concrete's specific density is mostly influenced by the aggregate's density; thus higher RA particle density results in higher concrete's specific density;
- The perceived higher open porosity of RA is the main cause of the higher water absorption by immersion in RA concrete;
- The use of superplasticizers resulted in a decreasing trend of concrete workability, suggesting that superplasticizers lose efficiency with increasing RA ratio;
- Compressive strength tends to decrease with the incorporation of RA, but the addition of superplasticizers can enhance the mix compactness, compensating for most of the strength loss;
- RA concrete revealed higher shrinkage strains than the RC (reference concrete, with NA only), however, superplasticizers, especially high performance water reducing ones, can partially mitigate the occurrence of this phenomenon in RA concrete;
- The use of superplasticizers allowed the carbonation depth of the RA concrete to be lower than that of the RC at early ages. Over time, the relative efficiency of both superplasticizers decreased in the RA concrete, even though the RA concrete with the high-performance superplasticizer always had lower carbonation depth than the

one with the standard superplasticizer;

- Mixes with RA and superplasticizers had better chloride penetration resistance than the RC. Adding superplasticizers can help to compact the cement paste, hindering the chloride penetration; however, there were some discrepancies in this test and further work is needed.

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Tables and Figures

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Table 1 - Properties of fine and coarse aggregates

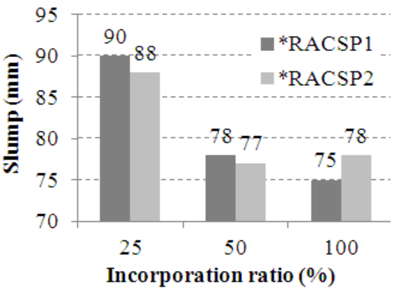
		Fine aggregates	**Coarse aggregates**		
			NA		**RA**
Apparent bulk density (kg/m^3)		1517	**Oven-dry**	-	1251
			Air-dry	1427	1256
Particle density (kg/m^3)	**Impermeable material**	2597	2687		2608
	Saturated surface-dry	2564	2652		2452
	Oven-dry particles	2544	2632		2355
Water absorption (%)		0.81	0.79		4.12

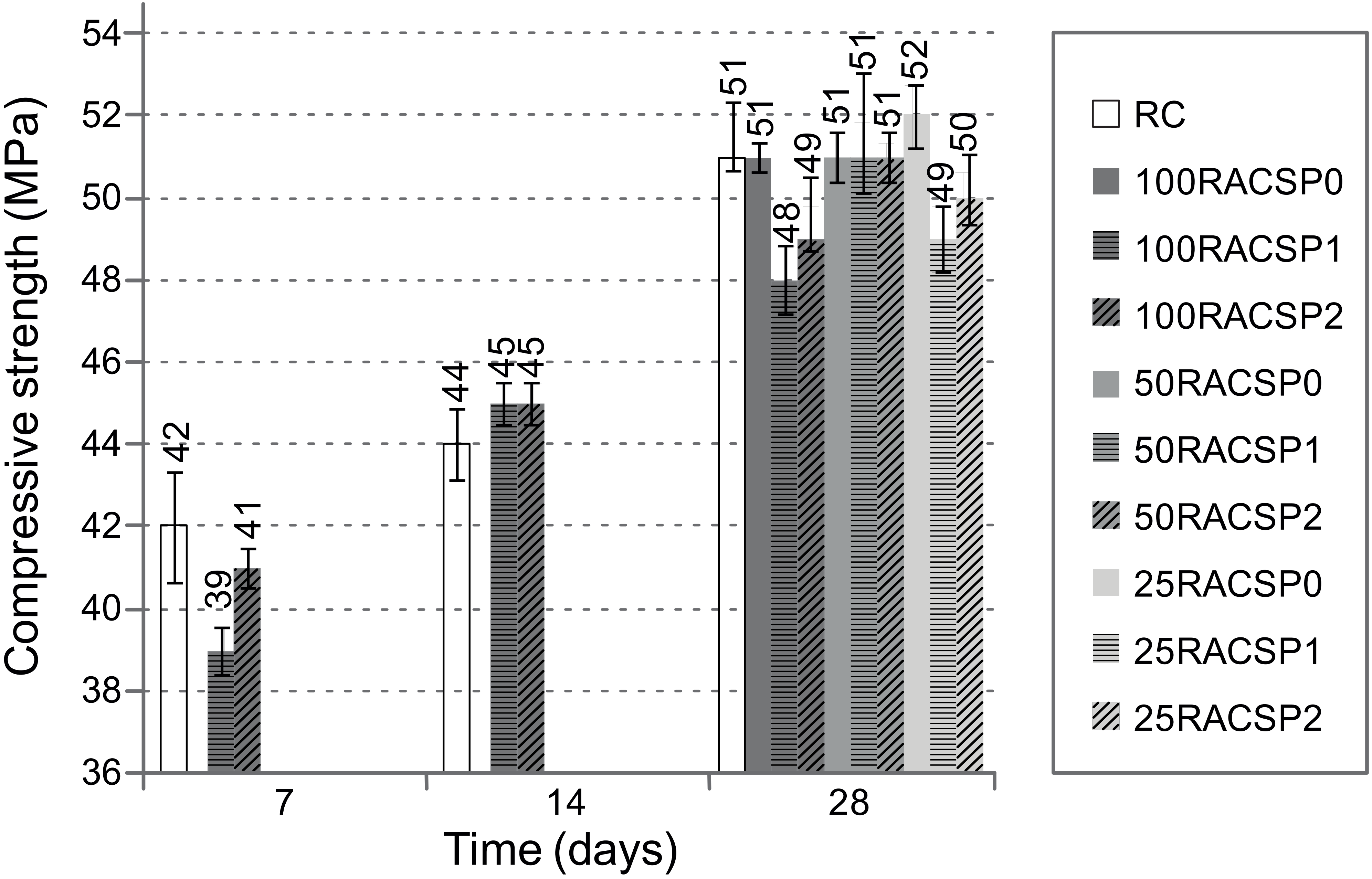
Table 2 - Mix composition of the RC and the RA concretes

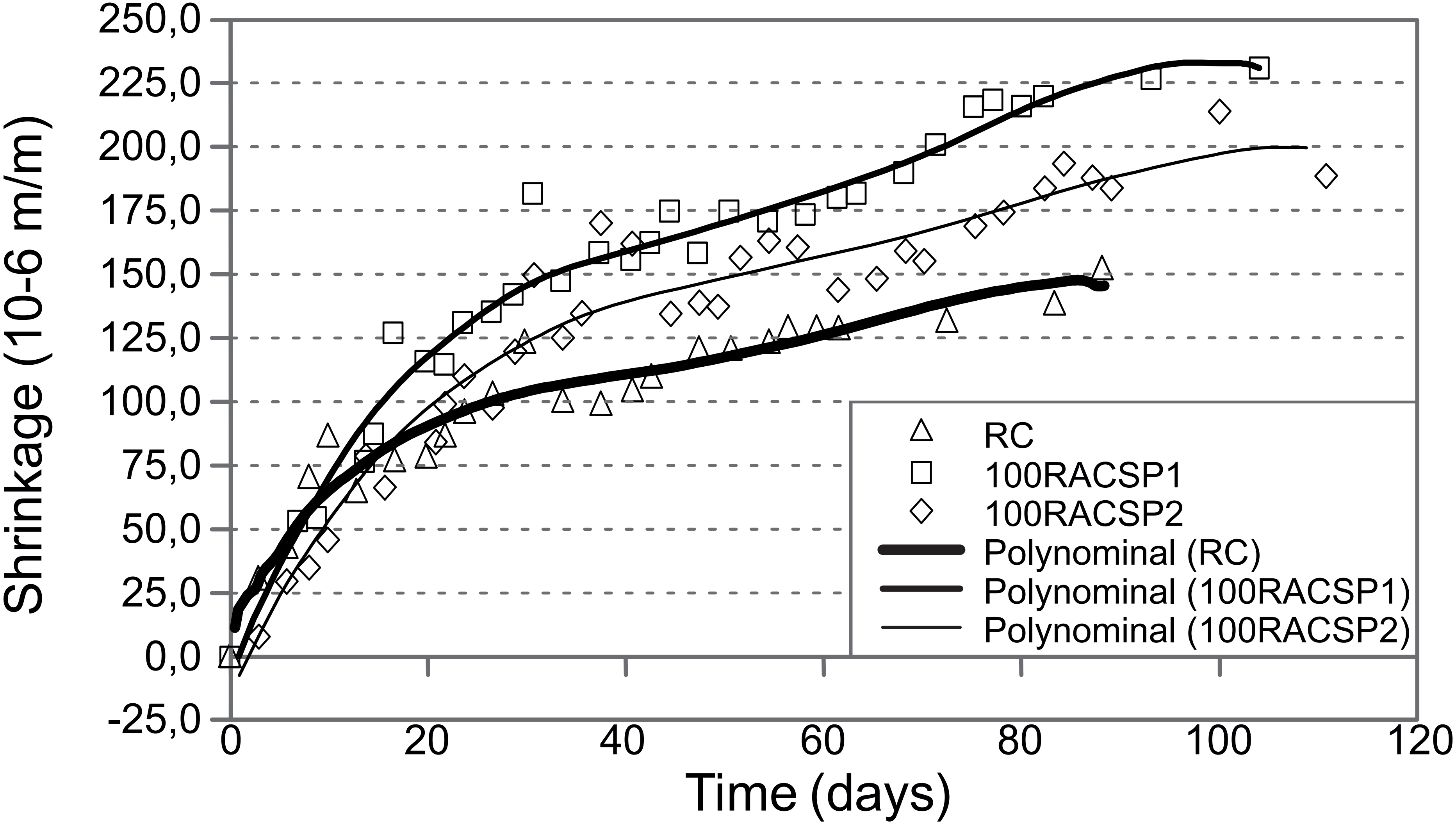
References		RC	100 RAC SP0	100 RAC SP1	100 RAC SP2	50 RAC SP0	50 RAC SP1	50 RAC SP2	25 RAC SP0	25 RAC SP1	25 RAC SP2
% of replacement		-	100	100	100	50	50	50	25	25	25
Cement II 42.5R (kg)		133				413					
Water (m^3)						206					
w/c		0.50	0.53			0.51			0.51		
w/c_{ef}						0.50					
		NA	**RA**			**NA**	**RA**		**NA**		**RA**
NA1 (kg)	**RA1 (kg)**	80	193			105	96		157		48
NA2 (kg)	**RA2 (kg)**	91	221			120	111		181		55
NA3 (kg)	**RA3 (kg)**	42	102			55	51		83		25
NA4 (kg)	**RA4 (kg)**	111	266			145	133		217		66
NA5 (kg)	**RA5 (kg)**	85	205			112	103		167		51
SP1 content (% of cement weight)		0	-	0.5	-	-	0.5	-	-	0.5	-
SP2 content (% of cement weight)		0	-	-	0.48	-	-	0.45	-	-	0.42

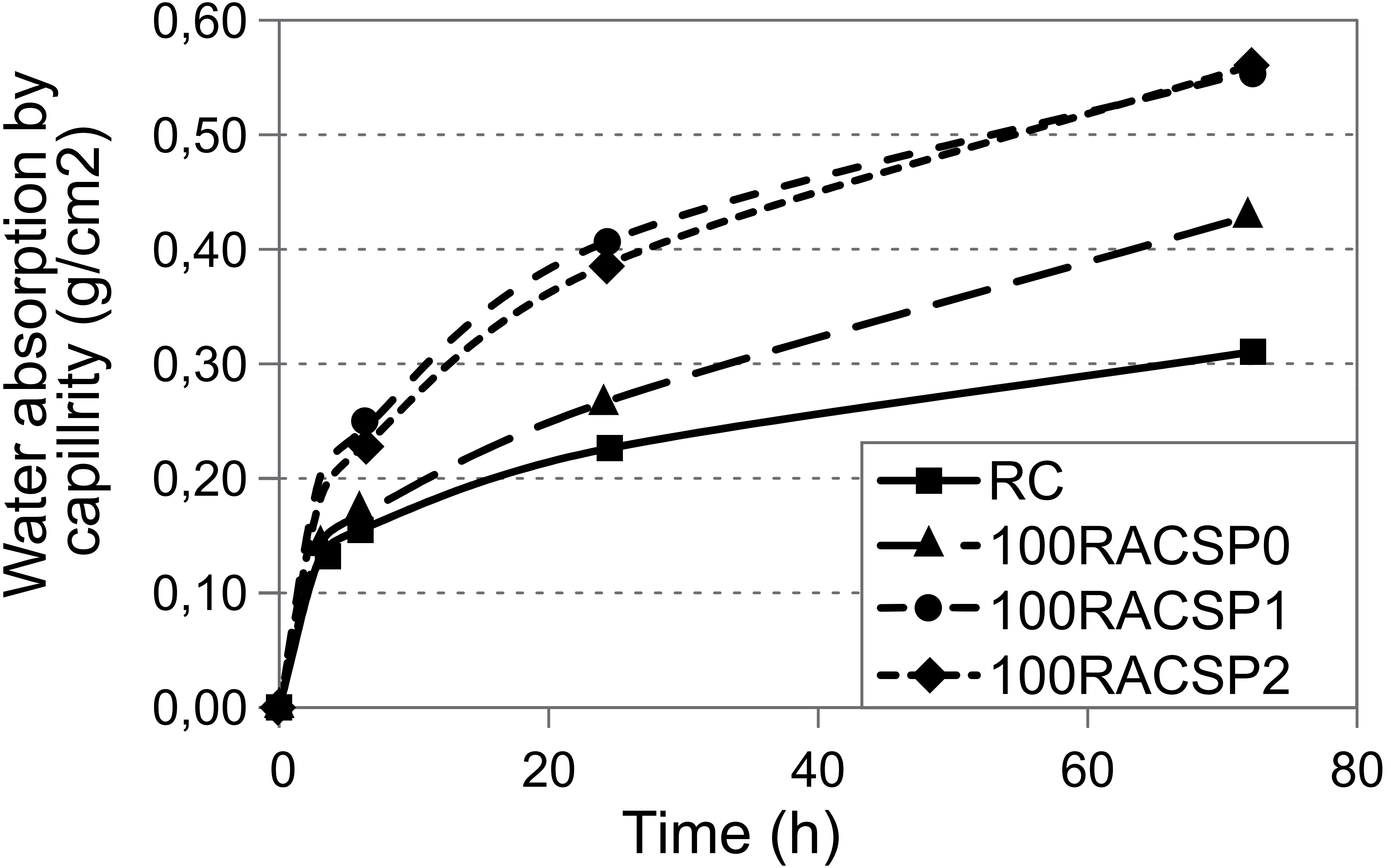
Note: RC is a concrete with 0% of RA and without superplasticizer.

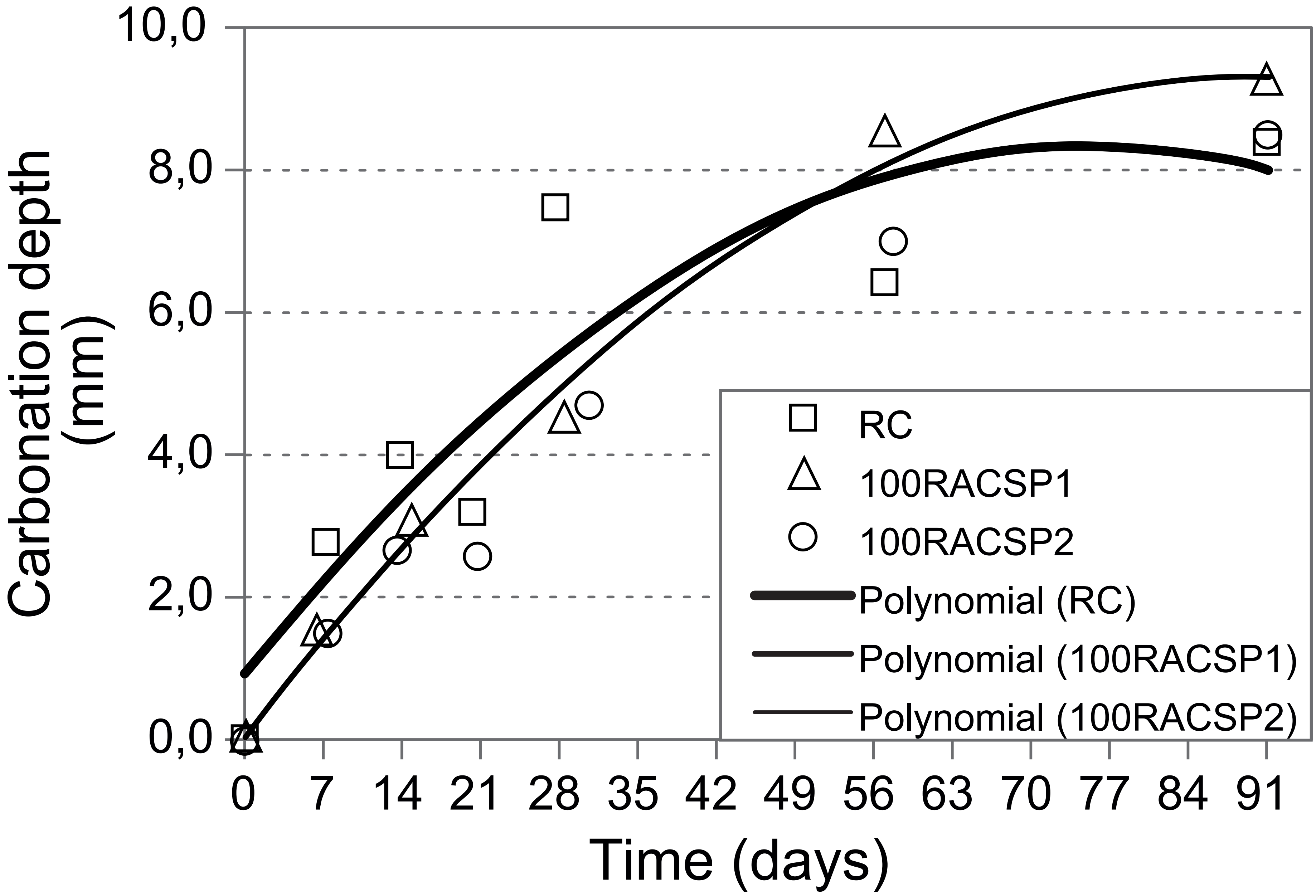
Table 3 - Concrete slump and specific density and SP1 mixes slump trend

Mix	Slump (mm)	Density (kg/m^3)	
RC	85	2350	
100RACSP0	62	2260	
100RACSP1	75	2237	
100RACSP2	78	2239	
50RACSP0	80	2300	
50RACSP1	78	2284	
50RACPSP2	77	2296	
25RACSP0	82	2332	
25RACSP1	90	2340	
25RACSP2	88	2308	


Compressive strength (MPa)
54
52
50
48
46
44
42
40
38
36
42
39
41
44
45
45
51
51
48
49
51
51
51
52
49
50
7
14
28
Time (days)
RC
100RACSP0
100RACSP1
100RACSP2
50RACSP0
50RACSP1
50RACSP2
25RACSP0
25RACSP1
25RACSP2


Shrinkage (10-6 m/m)
250,0
225,0
200,0
175,0
150,0
125,0
100,0
75,0
50,0
25,0
0,0
-25,0
0
20
40
60
80
100
120
Time (days)
RC
100RACSP1
100RACSP2
Polynominal (RC)
Polynominal (100RACSP1)
Polynominal (100RACSP2)


Water absorption by capillrity (g/cm2)
0,60
0,50
0,40
0,30
0,20
0,10
0,00
0
20
40
60
80
Time (h)
RC
100RACSP0
100RACSP1
100RACSP2


Carbonation depth (mm)
10,0
8,0
6,0
4,0
2,0
0,0
0
7
14
21
28
35
42
49
56
63
70
77
84
91
Time (days)
RC
100RACSP1
100RACSP2
Polynomial (RC)
Polynomial (100RACSP1)
Polynomial (100RACSP2)